



# Climate change and opposing spatial conservation priorities for anuran protection in the Brazilian hotspots

Tiago S. Vasconcelos<sup>a,\*</sup>, Vitor H.M. Prado<sup>b</sup>

<sup>a</sup> Departamento de Ciências Biológicas, Universidade Estadual Paulista, 17033-360 Bauru, SP, Brazil

<sup>b</sup> Campus Anápolis de Ciências Exatas e Tecnológicas Henrique Santillo, Universidade Estadual de Goiás, 75132-903 Anápolis, GO, Brazil

## ARTICLE INFO

### Keywords:

Atlantic Forest  
Cerrado  
Ecological niche modelling  
MARXAN software  
Spatial conservation prioritization

## ABSTRACT

In conservation biogeography, the process of spatial conservation prioritization (SCP) aims to select areas that meet biodiversity targets at a minimum set coverage. Here, we propose a SCP scheme for the highly endemic and diverse anuran fauna of the Atlantic Forest (AF) and Cerrado (CER) South American hotspots under different climate change scenarios. Specifically, we make use of predicted anuran occurrences, built for baseline and future (2050 and 2070) time slices, and address biological and conservation metrics to identify potential priority regions for anuran conservation over time using the software MARXAN. Considering each time slice separately, the percentage area needed for total anuran representation varies at magnitudes of 9.8–10.66% for the AF and 6.4–8.8% for the CER. Pooling all time slices together in the selected conservation network, the identified spatial priorities account for 15.56% and 13.25% of the total AF and CER areas respectively. However, we identified opposing strategies for the anuran spatial conservation prioritization in the AF and CER over the different time periods; the increasing of priority cells across time considering the potential species redistribution under climate change in the AF, and the selection of fewer priority cells in the future than the identified for the baseline climate in the CER. The southeastern AF coast was identified as a priority area for amphibian conservation in this hotspot, as well as some other smaller areas in the northern and southern regions. Priority areas identified in the CER, although patchy distributed across the hotspot, are found in specific central-northern, western, and southeastern regions. The different conservation strategies identified in the present SCP emphasize the need for establishing different conservation efforts according to a sequential scheduling of priority areas that optimizes the long-term conservation goals.

## 1. Introduction

Rates of biodiversity loss and degradation of ecosystems were more rapid in the past 50 years than at any time in Earth's evolutionary history. The main drivers of this biodiversity crisis are habitat change, overexploitation, pollution, invasive alien species, and climate change (Millennium Ecosystem Assessment, 2005). Currently, special attention has been given to climate change due to a wide range of biological responses exhibited from organisms to ecosystems to the already altered climatic conditions since the last 100 years, among them the species redistribution in the geographical space (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012; Pecl et al., 2017). Besides, we can intuitively predict the continuing of such biological responses because the projected increase in the mean temperature by 2100 (c. 1.5–2 °C) is about two times higher than that already documented in the last 100 years (c. 0.85°; Intergovernmental Panel on Climate Change

(IPCC), 2014). Therefore, it makes urgent the legal establishment of effective actions to protect biodiversity in a dynamic changing climate, so the integration of conservation biogeography and ecological niche modelling (ENM) methods have become important tools to mitigating climate-driven impacts on biodiversity (e.g., Aragón, Rodríguez, Olalla-Tárraga, & Lobo, 2010; Araújo, Alagador, Cabeza, Nogués-Bravo, & Thuiller, 2011; Chen, Zhang, Jiang, Nielsen, & He, 2017; Loyola et al., 2013).

ENMs essentially characterize the climatic niche of a given species within its known occurrence records. Further, projections of its climatic niche into a bioclimatic envelope of interest, such as future climate change scenarios, generate predictions of environmental suitability for the species (Araújo et al., 2011; Elith & Burgman, 2002). From a conservation point of view, the predicted species redistribution over different time periods can be implemented in conservation planning frameworks in order to generate specific and changing spatial

\* Corresponding author.

E-mail address: [anurofauna@yahoo.com.br](mailto:anurofauna@yahoo.com.br) (T.S. Vasconcelos).

<https://doi.org/10.1016/j.jnc.2019.04.003>

Received 18 September 2018; Received in revised form 6 March 2019; Accepted 15 April 2019

1617-1381/ © 2019 Elsevier GmbH. All rights reserved.

conservation priorities across time (Araújo & Peterson, 2012; Williams et al., 2005). Additionally, if ENMs are generated for a large number of species within a biogeographic region and for different climate change scenarios, the species distribution matrix can serve to identify spatial conservation priorities for a set of climate scenarios (e.g., Faleiro, Machado, & Loyola, 2013; Lemes & Loyola, 2013; Jones, Watson, Possingham, & Klein, 2016; Zwiener et al., 2017). Specifically, the identification of spatial priorities aims to select areas that meet biodiversity targets (e.g., species, functional, and/or phylogenetic diversity) at a minimum set coverage, which means that a comprehensive and efficient final reserve network contains every feature of biodiversity interest of a whole given area within a minimum number of selected sampling units (Ardrón, Possingham, & Klein, 2010; Kukkala & Moilanen, 2013 and references therein). At the end, the spatial conservation prioritization will be part of the whole process of systematic conservation planning that will finally locate, design, and manage protected areas for efficient biodiversity conservation (Ardrón et al., 2010; Kukkala & Moilanen, 2013).

In South America, the Atlantic Forest (AF) and Cerrado (CER) morphoclimatic domains (Ab'Sáber, 2003), largely found within Brazil's borders, are distinguished by their high levels of biodiversity and endemism. Yet, their high levels of anthropogenic habitat conversions led Mittermeier, Robles-Gil, Hoffmann, Pilgrim, Brooks, Mittermeier & da Fonseca, 2004 to recognize them as hotspots of biodiversity conservation. Among biological groups with high endemism rates within these hotspots, anuran amphibians are highly diverse in the AF, with 529 species and ~80% of endemism rates (Haddad et al., 2013). In the predominantly open vegetation formations of CER, the anuran diversity is less accentuated than in the AF, with 209 species, but the endemism rates are still high with 51.7% of them being endemic to this hotspot (Valdujo, Silvano, Colli, & Martins, 2012).

The present study aims to propose a spatial conservation prioritization for the highly endemic and diverse anuran fauna of the AF and CER South American hotspots. Previous prioritization schemes specifically performed for both hotspots, including anurans as biological models (Campos, Lourenço-de-Moraes, Llorente, & Solé, 2017; Silvano, Valdujo, & Colli, 2016) or not (Sobral et al., 2014), largely focused on current patterns of species distribution (but see Faleiro et al., 2013; Lemes & Loyola, 2013; Loyola et al., 2013; Zwiener et al., 2017). However, the general aims and methodology are highly variable among the studies. For instance, the only spatial prioritization scheme proposed for anurans in the CER considers the current patterns of species distribution, watersheds as sampling units, and addresses the evolutionary distinctiveness and distribution patterns as species attributes (Silvano et al., 2016). On the other hand, anuran conservation prioritizations proposed for the AF consider current and future predicted distributions, grid cells as planning units, and address species dispersal and methodological uncertainties to the final conservation proposal (Lemes & Loyola, 2013; Loyola et al., 2013). Therefore, the present study aims to propose spatial conservation priorities for climatically suitable areas of anurans at different time slices in the AF and CER addressing biological and human-related metrics that were rarely explored in previous studies within these regions: the uniqueness species composition of sampling units (i.e., the anuran beta diversity) and the human impacts in the environment that may cause difficulty for conservation efforts (e.g., Lagabriele, Lombard, Harris, & Livingstone, 2018). Then, the present conservation proposals were performed using the software MARXAN in order to prioritize sites: a) having unusual species composition of high conservation value, so we can integrate the diversity that accumulates from compositional differences between local species assemblages (Legendre, 2014; Socolar, Gilroy, Kunin, & Edwards, 2016); b) having low biodiversity costs for their recovery that were less impacted by anthropogenic habitat conversions; and c) sheltering threatened species according to the Brazilian Ministry of the Environment.

## 2. Materials and methods

### 2.1. Species data and ecological niche models

Distribution maps of AF and CER anurans were generated via ENM for three time periods (current, 2050, and 2070). Further, they were overlaid onto each grid cell of  $50 \times 50$  km of both hotspots, a resolution usually considered at this biogeographical scale (e.g., Loyola et al., 2013; Vasconcelos, Prado, da Silva, & Haddad, 2014), to generate a presence/absence matrix for each time slice. Then, each matrix was submitted to optimized procedures of spatial conservation prioritization. These data were generated and are fully described in Vasconcelos, do Nascimento, and Prado (2018), yet we will briefly summarize how they were gathered as follows.

A thorough point occurrence records of each 529 and 209 anuran species found in the AF (Haddad et al., 2013) and CER (Valdujo et al., 2012) were surveyed from three main sources: a) two open-access digital databases (the Global Biodiversity Facility: [www.gbif.org](http://www.gbif.org); the SpeciesLink project: <http://splink.cria.org.br>); b) museum and scientific collections: *Museu Nacional/Universidade Federal do Rio de Janeiro* (Rio de Janeiro, RJ, Brazil), *Museu de Zoologia da Universidade Federal da Bahia* (Salvador, BA, Brazil), *Coleção Herpetológica da Universidade Federal de Santa Maria* (Santa Maria, RS, Brazil), and the American Museum of Natural History (New York, NY, USA); and c) literature records. After removing duplicate and/or imprecise records, introduced species, and species with fewer than five occurrence records due to modelling limitations (e.g., Hernandez, Graham, Master, & Albert, 2006; Vasconcelos, Rodríguez, & Hawkins, 2012), ENMs were generated for 350 anuran species in the AF (totaling 18,798 occurrence points) and 155 species in the CER (totaling 16,385 occurrence points).

The species ENMs were modelled as a function of nine out of 19 climatic variables available in the WorldClim portal (<http://www.worldclima.org/version1>): mean diurnal range, isothermality, mean temperature of wettest quarter, mean temperature of driest quarter, precipitation of wettest month, precipitation of driest month, precipitation seasonality, precipitation of warmest quarter, and precipitation of coldest quarter. These variables, which have  $\sim 10$  km grid resolution, were selected because they have  $< 10.0$  variance inflation factors values, thus representing no collinearity problems for model building (Naimi & Araújo, 2016). The species climatic niches, based on the above-mentioned variables, were projected into future climate change scenarios (2050 and 2070) considering two representative concentration pathways (RCP2.6 and RCP8.5) and three atmosphere-ocean global circulation models (AOGCMs: the Community Climate System Model – CCSM4; the New Global Climate Model of the Meteorological Research Institute – MRI-CGCM3; and the Institute Pierre Simon Laplace – IPSL-CM5A-LR), all of them available at the WorldClim portal ([http://www.worldclima.org/cmip5\\_5m](http://www.worldclima.org/cmip5_5m)).

The modelling algorithms used to build the ENMs were: generalized linear models (GLM); boosted regression trees (BRT); random forests (RF); and support vector machines (SVM). According to the recommendations of Rangel and Loyola (2012) for the best practices in conservation planning, we chose these statistical (GLM) and machine-learning algorithms (BRT, RF, and SVM) to avoid commission errors (i.e., predictions of false positive) and to maximize precision in the final models. Because algorithms will still generate different predictions among them, each final species predictive map is an ensemble of model projections (see detailed procedures in the next paragraph). Additional descriptions and usefulness of each algorithm can be found elsewhere (Araújo et al., 2011; Elith et al., 2006; Naimi & Araújo, 2016; Rangel & Loyola, 2012; Vasconcelos, Antonelli, & Napoli, 2017, 2018). Absence records, required for model running for all selected algorithms, were considered as pseudo-absences randomly generated from the calibration area (Naimi & Araújo, 2016). The occurrence records were split at a proportion of 20–80% for model evaluation and calibration, respectively, and the two evaluation metrics performed were the area under

the curve (AUC) of the receiver operation characteristic and the true skill statistic (TSS) (Allouche, Tsoar, & Kadmon, 2006). Then, ENMs with  $AUC < 0.75$  or  $TSS < 0.3$  were excluded from the ensemble procedure.

The final species predictive maps for each time slice were based on the mean climatic suitability value per grid cell of the four algorithms for the baseline climate. The 2050 and 2070 predictions considered the mean value per grid cell of the four algorithms, three AOGCMs, and two RCPs. This ensemble approach is recommended to reconcile the inherent uncertainties generated from the use of different algorithms, AOGCMs, and RCPs (Alagador, Cerdeira, & Araújo, 2014; Araújo & New, 2007). The final climatic suitability species maps were converted into binary predictions based on the threshold values of the sensitivity-specificity equality approach (Liu, Berry, Dawson, & Pearson, 2005). The predictions made for the 2050 and 2070 climate scenarios considered the full-dispersal hypothesis (i.e., species have no constraint on dispersal; e.g., Luo, Jiang, & Tang, 2015) based on the following reasons: a) although anurans have limited dispersal capacity compared to other taxa (e.g., birds and mammals), dispersal ability is still highly variable among anurans (Wells, 2007), some of them are known to expand their areas of occurrence in cleared lands after deforestation in the AF (Haddad & Prado, 2005), and; b) since poleward/high altitude species range shifts have been widely recorded in the literature (e.g., Chen, Hill, Ohlemüller, Roy, & Thomas, 2011), gain in species richness or “invasion intensity” is an important recurring metric evaluated regarding the potential impacts of climate change on the distribution of biodiversity (Jones & Cheung, 2015; Lemes & Loyola, 2013; Molinos et al., 2015; Vasconcelos et al., 2018 and further discussion on the topic). Species and climate data preparation, model running, evaluation, and ensemble procedures were performed using the *sdm* package in the R environment (Naimi & Araújo, 2016).

## 2.2. Spatial conservation prioritization

We identified spatial conservation priorities across AF and CER hotspots using the software MARXAN (Ball & Possingham, 2000; Ball, Possingham, & Watts, 2009). Different conservation prioritizations were identified, separately for each time slice and hotspots, in order to have all anurans represented at a minimum possible cost, all of them based on the presence/absence species distribution matrix generated by ENMs (see similar procedure in Loyola et al., 2013). MARXAN uses a simulated annealing algorithm to configure areas that minimize the sum of the grid cells' costs while ensuring that the biodiversity targets are met. Here, the biodiversity targets aimed to find minimum representations of anuran species across the study area. That is, MARXAN selects planning units (i.e., grid cells) that are richer in species and/or complement each other, so their identifications are a combination that achieve the ultimate goal of containing every feature of biodiversity interest (i.e., all anuran species) (Ardron et al., 2010, and references therein). We also inform MARXAN to generate the search considering: a) the conservation costs addressed by the human footprint as a surrogate for biodiversity cost. That is, the human footprint index, downloaded at a resolution of  $1 \times 1$  km cell size, was averaged for each AF and CER grid cell to represent the combination of negative anthropogenic impacts on the environment (human population distribution, urban areas, roads, navigable rivers, and agricultural land uses; Wildlife Conservation Society - WCS, & Center for International Earth Science Information Network - CIESIN - Columbia University, 2005). Then, AF and CER grid cells with higher values of human footprint are less prioritized in the final solution because they represent highly altered areas with high biodiversity costs for their recovery; b) the higher conservation values for areas having significant *local contribution to beta diversity* (LCBD). The intention here is to consider those grid cells with unique species composition in assisting the present anuran prioritization schemes (e.g., Legendre, 2014; Socolar et al., 2016). Thus, we make use of the grid cells identified by Vasconcelos et al. (2018) having

significant LCBD to be prioritized in the final conservation solutions of each time period; and c) the higher conservation values for areas having threatened species based on the Brazilian Ministry of the Environment, document 444 of December 17th of 2014 (available at: [http://www.icmbio.gov.br/portal/images/stories/biodiversidade/fauna-brasileira/avaliacao-do-risco/PORTARIA\\_N%C2%BA\\_444\\_DE\\_17\\_DE\\_DEZEMBRO\\_DE\\_2014.pdf](http://www.icmbio.gov.br/portal/images/stories/biodiversidade/fauna-brasileira/avaliacao-do-risco/PORTARIA_N%C2%BA_444_DE_17_DE_DEZEMBRO_DE_2014.pdf)). In this case we pre-defined targets for each threatened species, so the respective grid cells where they occur are prioritized in the final solutions (e.g., Loyola et al., 2013).

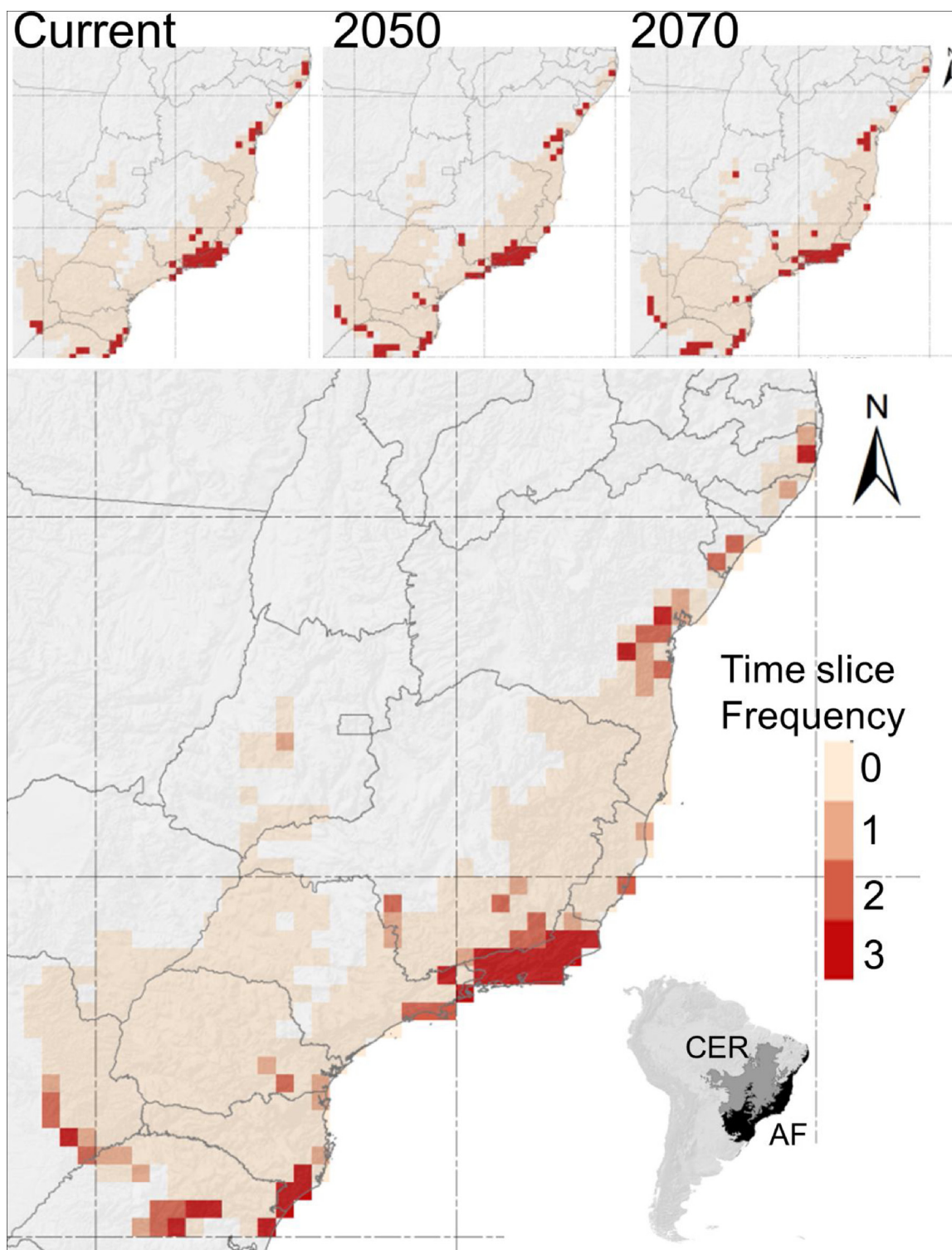
Because we are dealing with hundreds of planning units (grid cells) and hundreds of species, a high number of varying network solutions can be found among different optimization procedures. To meet the most frequent selected grid cells, we ran 100 procedures and identified the number of times that each grid cell was selected for each hotspot and climate scenario. Additionally, the boundary length modifier (BLM) was set to one, so a compacted/connected spatial solution is preferred over a patchy distribution of prioritized grid cells for each hotspot and climate scenario. The final prioritization schemes were then based on the summed solutions of the selection frequency that each grid cell was selected across the 100 runs (e.g. Ardron et al., 2010; Carvalho, Britto, Crespo, & Possingham, 2011; Runge, Tulloch, Possingham, Tulloch, & Fuller, 2016). Specifically, we considered a grid cell in the final prioritization scheme those ones selected in more than 50% of the runs due to their efficiency in meeting biodiversity goals in most optimization procedures (Ardron et al., 2010). Finally, the spatial congruence among the prioritization schemes of the different time periods, based on the selection frequency number of each grid cell across the 100 runs, was calculated by the Bray-Curtis index of dissimilarity (e.g., Runge et al., 2016).

## 3. Results

We found that anurans in the AF can be totally represented by 46 of the 469 grid cells (~9.81%) considering the baseline climate, whereas all CER anurans are represented by 62 of the 702 grid cells (~8.83%) (Figs. 1 and 2). Considering the future climate change scenarios, opposing strategies for the anuran spatial conservation prioritization should be taken in the AF and CER. In the AF, an addition of eight and four grid cells are needed to represent all anurans by 2050 and 2070, thus accounting for 11.51% and 10.66% of the total AF grid cells, respectively. Out of the 46 cells selected for the baseline climate, ~61% (28 grid cells) are also presumed to be biologically important for AF anurans in future climate change scenarios (Fig. 1). Oppositely, a decreased number of grid cells are presumed to represent all anurans in the CER by 2050 (45 grid cells) and 2070 (48 grid cells), thus accounting for 6.41% and 6.84% of the total CER grid cells, respectively. Out of the 62 cells initially selected for the baseline climate, only ~32% of them (20 grid cells) are also presumed to be of relevance for anuran conservation in the CER across all time frames (Fig. 2).

The spatial congruence of the summed frequencies of prioritization solutions among the different time slices varies at a magnitude of 65–76% of similarity in the AF and 70–80% in the CER (Table 1). These congruent spatial priorities in the AF (i.e., priority cells selected for all climate scenarios) are mainly concentrated in the southeastern Atlantic coast. To a lesser extent, some spatial congruencies are also found in the far northern and southern region of the AF (Fig. 1). All other spatial priorities identified for the AF are patchily distributed across the hotspot and mainly important for one or two specific time slices. In the CER, these congruent spatial priority cells have a patchier distribution than in the AF, but some concentration of grid cells identified as important for all climate scenarios can be found in the western, northern, and southeastern regions of the CER (Fig. 2). The central portion of the CER has also a concentration of priority cells, but mainly important for one or two specific climate scenarios (Fig. 2).



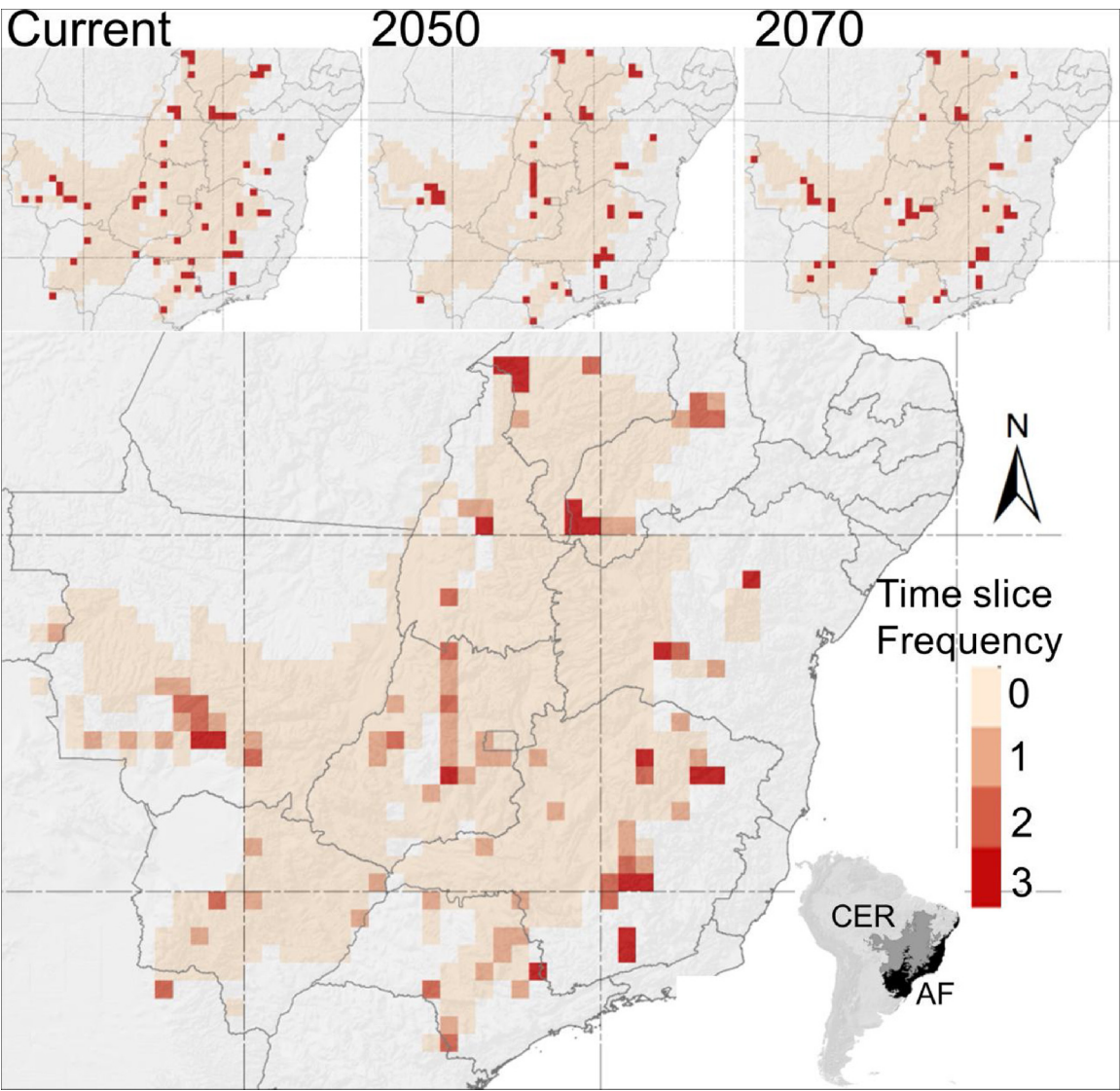


**Fig. 1.** Priority areas for anuran conservation in the Atlantic Forest for the different climate scenarios (baseline-current, 2050, and 2070). Upper maps represent binary priority areas for each time slice, whereas the larger lower map represents the frequency histogram of the binary maps across current, 2050, and 2070 climate scenarios.

#### 4. Discussion

The main findings of the present study are that the conservation targets reached for the AF include the increasing of priority cells across time considering the potential species redistribution under climate change, whereas the conservation targets reached for the CER require the selection of less priority cells in the future than the identified for the

baseline climate. [Alagador et al. \(2014\)](#) propose a sequential scheduling of priority identification that optimizes long-term conservation goals under climate change, which includes the release of some areas when they stop contributing to the specific long-term conservation goals. This releasing conservation strategy of selected areas can be mainly applied here for the baseline climate priority cells identified for the CER that will presumably no longer contribute to the anuran conservation targets



**Fig. 2.** Priority areas for anuran conservation in the Cerrado for the different climate scenarios (baseline-current, 2050, and 2070). Upper maps represent binary priority areas for each time slice, whereas the larger lower map represents the frequency histogram of the binary maps across current, 2050, and 2070 climate scenarios.

**Table 1**  
Spatial similarity (100 – Bray-Curtis dissimilarity: 100% = completely similar, 0% = completely dissimilar) between pairs of climate scenarios (current, 2050, and 2070) of the resulting summed selection frequency after 100 runs in MARXAN.

	AF		CER	
	Current	2050	Current	2050
2050	69.70	–	71.93	–
2070	65.34	76	70.81	80.24

under climate change. The selection of fewer grid cells under climate change in the CER is probably a reflection of the predicted compositional homogenization of anurans in the future, as indicated by the lowest beta diversity dissimilarity values in future scenarios in this hotspot (Vasconcelos et al., 2018), so the selection of fewer areas is expected to sufficiently represent all species in this hotspot. Alternatively, conservation actions in the AF should involve an increase of conservation areas by 2050 and 2070 in order to reach the conservation goals across time. That means that a selection of additional priority

areas, compared to the spatial conservation network identified for the baseline climate, is recommended in the AF to fully accomplish the future conservation targets. Moreover, an efficient conservation delineation proposed herein is to prioritize those cells selected in all climate scenarios in order to maximize the persistence of anuran diversity across time. Additional connectivity approaches would also be very helpful in identifying corridors among our selected grid cells for biodiversity connectivity (e.g., Alagador et al., 2012; Brás, Cerdeira, Alagador, & Araújo, 2013) through shifting climatic suitability (Williams et al., 2005).

The spatial conservation prioritizations for some biological groups (e.g., amphibians, birds, and mammals) considering only current patterns of species distribution, although having different general goals and analytical methods, have repeatedly pointed to the southeastern coast of the AF as being a priority area for biological conservation (Brum et al., 2017; Campos et al., 2017; Dobrovolski, Loyola, da Fonseca, Diniz-Filho, & Araújo, 2014; Moilanen, Anderson, Arponen, Pouzols, & Thomas, 2013; Sobral et al., 2014). Other studies considering the predicted species redistribution under climate change have also identified the southeastern AF coast as a priority area for conservation purposes in the future (Lemes & Loyola, 2013; Loyola et al.,

2013; Zwiener et al., 2017). The present study corroborates these previous findings and specifically identifies the coastal area of the states of São Paulo and Rio de Janeiro as having high priority for long-term amphibian protection. Fortunately, the southeastern AF close to the Atlantic coast has already been reasonably covered by legally protected areas compared to the entire hotspot (see Campos et al., 2017), which may thus help the conservation efforts in this area. Additional areas selected in the present study for the northern AF were already identified as priority areas for amphibian protection under climate change (Lemes & Loyola, 2013; Loyola et al., 2013), though the present study identifies a wider northern AF area than these studies. We also identified important areas for anuran conservation in southern AF areas that are misrepresented in previous anuran spatial conservation prioritizations (Lemes & Loyola, 2013; Loyola et al., 2013). Although this incongruence may be accounted for the differences in the study design and applied methodology among studies, we highlight the importance of selecting these southern AF areas to the final conservation proposal because these areas shelter different species pools that are not sufficiently represented in other ecoregions (e.g. Vasconcelos et al., 2014).

Previous spatial conservation prioritizations encompassing the CER hotspot are largely performed for the current time, thus not considering the potential species redistribution under climate change. Although considered either for global, national, or regional approaches, as well as having different specific aims and analytical methodology, these studies broadly identify the central-northern CER regions of high conservation value for amphibians, birds, and mammals (Dobrovolski et al., 2014; Moilanen et al., 2013; Silvano et al., 2016; Sobral et al., 2014). Considering the different climate change scenarios, we also found some central-northern CER areas as being of high conservation value across time. All else being equal, some western and southeastern CER areas were also identified here as having high conservation priority, yet they are misrepresented and/or absent in previous conservation prioritizations that did not consider global climate change (Dobrovolski et al., 2014; Moilanen et al., 2013; Silvano et al., 2016; Sobral et al., 2014). Thus, the present study presents the first spatial conservation prioritization specifically designed for the anuran conservation in the CER addressing the potential climate-driven impacts on the species distribution. This is important because these animals' life histories are tightly linked to environmental conditions (Wells, 2007), so the predicted changes in the patterns of anuran distribution can be highly useful for future effective conservation actions. Taken together, we emphasize that all prioritized areas selected herein are not meant to be fully protected in their each 50 × 50 km extent. Rather, they represent areas in which further local efforts should be directed for the searching of specific locations to protect (Moilanen et al., 2013).

Considering each time period separately, the percentage area needed for total anuran representation varies at magnitudes of 9.8–10.66% for the AF and 6.4–8.8% for the CER. Pooling all time slices together in the selected conservation network, the identified spatial priorities increase to 15.56% and 13.25% of the total AF and CER areas, respectively. Following the recommendation to setting a minimum of 17% of a terrestrial ecosystem area as legally protected (Harrop, 2011), the present conservation proposal still needs to select additional grid cells to reach that target. The present study addressed some important conservation features and targets to propose the prioritization scheme for anurans in the AF and CER hotspots, such as the anthropogenic impacts across the study area, the prioritization of areas having unique species composition and also those that shelter threatened species. Nonetheless, a maximized spatial conservation planning that would certainly help in achieving the 17% target should consider additional biological metrics and/or corridors among the selected areas that maintain some specific population and community dynamics (e.g., Alagador et al., 2012; Brás et al., 2013). To do so, the inclusion of a maximum number of taxa and the incorporation of functional and phylogenetic diversity (e.g. Campos et al., 2017; Carvalho et al., 2017), as well as the consideration of future deforestation scenarios into more

precise modelling procedures for those species highly dependent on the habitat structure (e.g., Gouveia, 2016; Triviño, Thuiller, Cabeza, Hickler, & Araújo, 2011), are important approaches that address the multiple facets of biological diversity. The present study and all these approaches bring together important, well-funded, and complementary information for the decision-makers to elaborate a final systematic conservation planning for threatened areas, such as the South American Atlantic Forest and Cerrado hotspots, which is currently urgent in light of such rapid climate change that we are experiencing.

## Funding

This study was supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP, grants n. 2011/18510-0, 2012/07765-0) and is part of the FAPESP Research Program on Global Climate Change (RPGCC). TSV was also supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, grant n. 114613/2018-4). VHMP's research is supported by the University Research and Scientific Production Support Program (PROBIP/UEG) and by CNPq (grant n. 431012/2016-4).

## References

- Ab'Sáber, A. (2003). *Os domínios de natureza no Brasil: potencialidades paisagísticas*. São Paulo: Ateliê Editorial.
- Alagador, D., Triviño, M., Cerdeira, J. O., Brás, R., Cabeza, M., & Araújo, M. B. (2012). Linking like with like: Optimising connectivity between environmentally-similar habitats. *Landscape Ecology*, 27, 291–301.
- Alagador, D., Cerdeira, J. O., & Araújo, M. B. (2014). Shifting protected areas: Scheduling spatial priorities under climate change. *The Journal of Applied Ecology*, 51, 703–713. <https://doi.org/10.1111/1365-2664.12230>.
- Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and true skill statistic (TSS). *The Journal of Applied Ecology*, 43, 1223–1232. <https://doi.org/10.1111/j.1365-2664.2006.01214.x>.
- Aragón, P., Rodríguez, M.Á., Olalla-Tárraga, M. A., & Lobo, J. M. (2010). Predicted impact of climate change on threatened terrestrial vertebrates in central Spain highlights differences between endotherms and ectotherms. *Animal Conservation*, 13, 363–373. <https://doi.org/10.1111/j.1469-1795.2009.00343.x>.
- Araújo, M. B., & New, M. (2007). Ensemble forecasting of species distributions. *Trends in Ecology & Evolution*, 22, 42–47. <https://doi.org/10.1016/j.tree.2006.09.010>.
- Araújo, M. B., & Peterson, A. T. (2012). Uses and misuses of bioclimatic envelope modeling. *Ecology*, 93, 1527–1539. <https://doi.org/10.1890/11-1930.1>.
- Araújo, M. B., Alagador, D., Cabeza, M., Nogués-Bravo, D., & Thuiller, W. (2011). Climate change threatens European conservation areas. *Ecology Letters*, 14, 484–492. <https://doi.org/10.1111/j.1461-0248.2011.01610.x>.
- Ardron, J. A., Possingham, H. P., & Klein, C. J. (2010). *Marxan good practices handbook*. Version 2. Victoria: Pacific Marine Analysis and Research Association.
- Ball, I. R., & Possingham, H. P. (2000). *Marxan (v 1.8.6): Marine reserve design using spatially explicit annealing. A Manual Prepared for the Great Barrier Reef Marine Park Authority*.
- Ball, I. R., Possingham, H. P., & Watts, M. (2009). Marxan and relatives: Software for spatial conservation prioritisation. In A. Moilanen, K. A. Wilson, & H. P. Possingham (Eds.). *Spatial conservation prioritisation: Quantitative methods and computational tools* (pp. 185–195). Oxford: Oxford University Press.
- Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, 15, 365–377. <https://doi.org/10.1111/j.1461-0248.2011.01736.x>.
- Brás, R., Cerdeira, J. O., Alagador, D., & Araújo, M. B. (2013). Linking habitats for multiple species. *Environmental Modelling & Software*, 40, 336–339.
- Brum, F. T., Graham, C. H., Costa, G. C., Hedges, S. B., Penone, C., Radeloff, V. C., ... Davidson, A. D. (2017). Global priorities for conservation across multiple dimensions of mammalian diversity. *PNAS*, 114, 7641–7646.
- Campos, F. S., Lourenço-de-Moraes, R., Llorente, G. A., & Solé, M. (2017). Cost-effective conservation of amphibian ecology and evolution. *Science Advances*, 3, e1602929.
- Carvalho, S. B., Britto, J. C., Crespo, E. J., & Possingham, H. P. (2011). Incorporating evolutionary processes into conservation planning using species distribution data: A case study with the western Mediterranean herpetofauna. *Diversity & Distributions*, 17, 408–421. <https://doi.org/10.1111/j.1472-4642.2011.00752.x>.
- Carvalho, S. B., Velo-Antón, G., Tarraso, P., Portela, A. P., Barata, M., Carranza, S., ... Possingham, H. P. (2017). Spatial conservation prioritization of biodiversity spanning the evolutionary continuum. *Nature Ecology and Evolution*, 1(2017), 0151. <https://doi.org/10.1038/s41559-017-0151>.
- Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science*, 333, 1024–1026. <https://doi.org/10.1126/science.1206432>.
- Chen, Y., Zhang, J., Jiang, J., Nielsen, S. E., & He, F. (2017). Assessing the effectiveness of China's protected areas to conserve current and future amphibian diversity. *Diversity & Distributions*, 23, 146–157. <https://doi.org/10.1111/ddi.12508>.



- Dobrovolski, R., Loyola, R., da Fonseca, G. A. B., Diniz-Filho, J. A. F., & Araújo, M. B. (2014). Globalizing conservation efforts to save species and enhance food production. *BioScience*, 64, 539–545. <https://doi.org/10.1093/biosci/biu064>.
- Elith, J., & Burgman, M. A. (2002). Predictions and their validation: Rare plants in the Central Highlands, Victoria, Australia. In J. M. Scott, P. J. Heglund, M. L. Morrison, M. G. Raphael, W. A. Wall, & F. B. Samson (Eds.). *Predicting species occurrences: Issues of scale and accuracy* (pp. 303–314). Covello: Island Press.
- Elith, J., Graham, C. H., Anderson, R. P., Dudík, M., Ferrier, S., Guisan, A., ... Zimmermann, N. E. (2006). Novel methods improve prediction of species' distribution from occurrence data. *Ecography*, 29, 129–151. <https://doi.org/10.1111/j.2006.0906-7590.04596.x>.
- Faleiro, F. V., Machado, R. B., & Loyola, R. D. (2013). Defining spatial conservation priorities in the face of land-use and climate change. *Biological Conservation*, 158, 248–257.
- Gouveia, S. F. (2016). Climate and land use changes will degrade the configuration of the landscape for titi monkeys in Brazil. *Global Change Biology*, 22, 2003–2012. <https://doi.org/10.1111/gcb.13162>.
- Haddad, C. F. B., & Prado, C. P. A. (2005). Reproductive modes in frogs and their unexpected diversity in the Atlantic Forest of Brazil. *BioScience*, 55, 207–217.
- Haddad, C. F. B., Toledo, L. F., Prado, C. P. A., Loebmann, D., Gasparini, J. L., & Sazima, I. (2013). *Guide to the amphibians of the Atlantic Forest: Diversity and biology*. São Paulo: Anolis Books.
- Harrop, S. R. (2011). Living in harmony with nature? Outcomes of the 2010 Nagoya conference of the convention on biological diversity. *Journal of Environmental Law*, 23, 117–128.
- Hernandez, P. A., Graham, C. H., Master, L. L., & Albert, D. L. (2006). The effect of sample size and species characteristics on performance of different species distribution modeling methods. *Ecography*, 29, 773–785. <https://doi.org/10.1111/j.0906-7590.2006.04700.x>.
- Intergovernmental Panel on Climate Change (IPCC) (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change* Available at [www.ipcc.ch/report/ar5/syr/](http://www.ipcc.ch/report/ar5/syr/).
- Jones, M. C., & Cheung, W. W. L. (2015). Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES Journal of Marine Science*, 72, 741–752. <https://doi.org/10.1093/icesjms/fsu172>.
- Jones, K. R., Watson, J. E. M., Possingham, H. P., & Klein, C. J. (2016). Incorporating climate change into spatial conservation prioritization: A review. *Biological Conservation*, 194, 121–130.
- Kukkala, A. S., & Moilanen, A. (2013). Core concepts of spatial prioritization in systematic conservation planning. *Biological Reviews of the Cambridge Philosophical*, 88, 443–464. <https://doi.org/10.1111/brv.12008>.
- Lagabriele, E., Lombard, A. T., Harris, J. M., & Livingstone, T.-C. (2018). Multi-scale multi-level marine spatial planning: A novel methodological approach applied in South Africa. *PLoS One*, 13, e0192582. <https://doi.org/10.1371/journal.pone.0192582>.
- Legendre, P. (2014). Interpreting the replacement and richness difference components of beta diversity. *Global Ecology and Biogeography*, 23, 1324–1334. <https://doi.org/10.1111/geb.12207>.
- Lemes, P., & Loyola, R. D. (2013). Accommodating species climate-forced dispersal and uncertainties in spatial conservation planning. *PLoS One*, 8(1), e54323. <https://doi.org/10.1371/journal.pone.0054323>.
- Liu, C., Berry, P. M., Dawson, T. P., & Pearson, R. G. (2005). Selecting thresholds of occurrence in the prediction of species distributions. *Ecography*, 28, 385–393. <https://doi.org/10.1111/j.0906-7590.2005.03957.x>.
- Loyola, R. D., Lemes, P., Nabout, J. C., Trindade-Filho, J., Sagnori, M. D., Dobrovolski, R., ... Diniz-Filho, J. A. F. (2013). A straightforward conceptual approach for evaluating spatial conservation priorities under climate change. *Biodiversity and Conservation*, 22, 483–495. <https://doi.org/10.1007/s10531-012-0424-x>.
- Luo, Z., Jiang, Z., & Tang, S. (2015). Impacts of climate change on distributions and diversity of ungulates on the Tibetan Plateau. *Ecological Applications*, 25, 24–38.
- Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: Biodiversity synthesis*. Washington: World Resources Institute.
- Mittermeier, R. A., Robles-Gil, P., Hoffmann, M., Pilgrim, J. D., Brooks, T. B., Mittermeier, C. G., ... da Fonseca, G. A. B. (2004). *Hotspots revisited: Earths biologically richest and most endangered ecoregions*. Mexico City: CEMEX.
- Moilanen, A., Anderson, B. J., Arponen, A., Pouzols, F. M., & Thomas, C. D. (2013). Edge artefacts and lost performance in national versus continental conservation priority areas. *Diversity & Distributions*, 19, 171–183.
- Molinos, J. G., Halpern, B. S., Schoeman, D. S., Brown, C. J., Kiessling, W., Moore, P. J., ... Burrows, M. T. (2015). Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, 6, 83–88. <https://doi.org/10.1038/NCLIMATE2769>.
- Naimi, B., & Araújo, M. B. (2016). Sdm: A reproducible and extensible R platform for species distribution modelling. *Ecography*, 39, 368–371. <https://doi.org/10.1111/ecog.01881>.
- Peel, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., ... Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355. <https://doi.org/10.1126/science.aai9214>.
- Rangel, T. F., & Loyola, R. D. (2012). Labeling ecological niche models. *Natureza & Conservação*, 10, 119–126. <https://doi.org/10.4322/natcon.2012.030>.
- Runge, C. A., Tulloch, A. I. T., Possingham, H. P., Tulloch, V. J. D., & Fuller, R. A. (2016). Incorporating dynamic distributions into spatial prioritization. *Diversity & Distributions*, 22, 332–343.
- Silvano, D. L., Valdujo, P. H., & Colli, G. R. (2016). Priorities for conservation of the evolutionary history of amphibians in the Cerrado. In R. Pellens, & P. Grandcolas (Eds.). *Biodiversity conservation and phylogenetic systematics: Preserving our evolutionary heritage in an extinction crisis* (pp. 287–304). Springer International Publishing.
- Sobral, F. L., Jardim, L., Lemes, P., Machado, N., Loyola, R., & Cianciaruso, M. V. (2014). Spatial conservation priorities for top predators reveal mismatches among taxonomic, phylogenetic and functional diversity. *Natureza & Conservação*, 12, 150–155.
- Socolar, J. B., Gilroy, J. J., Kunin, W. E., & Edwards, D. P. (2016). How should beta-diversity inform biodiversity conservation? *Trends in Ecology & Evolution*, 31, 67–80. <https://doi.org/10.1016/j.tree.2015.11.005>.
- Trivinho, M., Thuiller, W., Cabeza, M., Hickler, T., & Araújo, M. B. (2011). The contribution of vegetation and landscape configuration for predicting environmental change impacts on Iberian birds. *PLoS One*, 6, e29373. <https://doi.org/10.1371/journal.pone.0029373>.
- Valdujo, P. H., Silvano, D. L., Colli, G., & Martins, M. (2012). Anuran species composition and distribution patterns in the Brazilian Cerrado, a neotropical hotspot. *South American Journal of Herpetology*, 7, 63–78. <https://doi.org/10.2994/057.007.0209>.
- Vasconcelos, T. S., Rodríguez, M. A., & Hawkins, B. A. (2012). Species distribution modelling as a macroecological tool: A case study using New World amphibians. *Ecography*, 35, 539–548. <https://doi.org/10.1111/j.1600-0587.2011.07050.x>.
- Vasconcelos, T. S., Prado, V. H. M., da Silva, F. R., & Haddad, C. F. B. (2014). Biogeographic distribution patterns and their correlates in the diverse frog fauna of the Atlantic Forest hotspot. *PLoS One*, 9(8), e104130. <https://doi.org/10.1371/journal.pone.0104130>.
- Vasconcelos, T. S., Antonelli, C. P., & Napoli, M. F. (2017). Mutualism influences species distribution predictions for a bromeliad-breeding anuran under climate change. *Austral Ecology*, 42, 869–877. <https://doi.org/10.1111/aec.12509>.
- Vasconcelos, T. S., do Nascimento, B. T. M., & Prado, V. H. M. (2018). Expected impacts of climate change threaten the anuran diversity in the Brazilian hotspots. *Ecology and Evolution*, 8, 7894–7909. <https://doi.org/10.1002/ece3.4357>.
- Wells, K. D. (2007). *The ecology and behavior of amphibians*. Chicago: The University of Chicago Press.
- Wildlife Conservation Society - WCS, and Center for International Earth Science Information Network - CIESIN - Columbia University (2005). *Last of the wild project, version 2, 2005 (LWP-2): Global human footprint dataset (Geographic)*.
- Williams, P., Hannah, L., Andelman, S., Midgley, G., Araújo, M., Hughes, G., ... Pearson, R. (2005). Planning for climate change: Identifying minimum-dispersal corridors for the Cape Proteaceae. *Conservation Biology*, 19, 1063–1074.
- Zwiener, V. P., Padial, A. A., Marques, M. C. M., Faleiro, F. V., Loyola, R., & Peterson, A. T. (2017). Planning for conservation and restoration under climate and land use change in the Brazilian Atlantic forest. *Diversity & Distributions*, 23, 955–966.